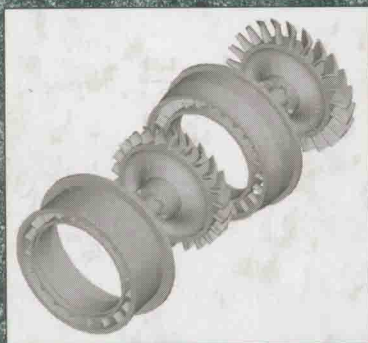


THIRD EUROPEAN CONFERENCE ON  
TURBOMACHINERY:  
FLUID DYNAMICS  
AND  
THERMODYNAMICS  
VOLUME B



# IMechE Conference Transactions

---



Third European Conference on

## **Turbomachinery – Volume B** **Fluid Dynamics and Thermodynamics**

2–5 March 1999

Royal National Hotel, London, UK

Organized by the Energy Transfer and Thermofluid Mechanics Group of the  
Institution of Mechanical Engineers (IMechE)

With support and sponsorship from

European Commission

Rolls-Royce plc

ALSTOM Energy Limited

ALSTOM Technology Centre

ALSTOM Gas Turbines Limited



**IMechE Conference Transactions 1999–1B**



Published by Professional Engineering Publishing Limited for the Institution of  
Mechanical Engineers, Bury St Edmunds and London, UK.

## First Published 1999

This publication is copyright under the Berne Convention and the International Copyright Convention. All rights reserved. Apart from any fair dealing for the purpose of private study, research, criticism or review, as permitted under the Copyright, Designs and Patents Act, 1988, no part may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, electrical, chemical, mechanical, photocopying, recording or otherwise, without the prior permission of the copyright owners. Reprographic reproduction is permitted only in accordance with the terms of licences issued by the Copyright Licensing Agency, 90 Tottenham Court Road, London W1P 9HE. *Unlicensed multiple copying of the contents of this publication is illegal.* Inquiries should be addressed to: The Publishing Editor, Professional Engineering Publishing Limited, Northgate Avenue, Bury St. Edmunds, Suffolk, IP32 6BW, UK. Fax: 01284 704006.

© The Institution of Mechanical Engineers 1999, unless otherwise stated.

ISSN 1356-1448  
ISBN 1 86058 196 X

A CIP catalogue record for this book is available from the British Library.

Printed and bound in Great Britain by Antony Rowe Limited, Chippenham, Wiltshire, UK.

The Publishers are not responsible for any statement made in this publication. Data, discussion, and conclusions developed by authors are for information only and are not intended for use without independent substantiating investigation on the part of potential users. Opinions expressed are those of the Author and are not necessarily those of the Institution of Mechanical Engineers or its Publishers.

**Turbomachinery – Volume B**

## Conference Organizing Committee

**D Bohn**  
Aachen, Germany

**G Bois**  
Ecully, France

**M Davies**  
Limerick, Ireland

**R Decuyper**  
Brussels, Belgium

**G Dibelius**  
Aachen, Germany

**R Dunker**  
EC

**T Fransson**  
Stockholm, Sweden

**G Gyarmathy**  
Zurich, Switzerland

**B Haller**  
Lincoln, UK  
(Local Organizer)

**E G Hencke**  
Dusseldorf, Germany

**H Jericha**  
Graz, Austria

**J Krzyanowski**  
Gdansk, Poland

**F Martelli**  
Firenze, Italy

**V Molnar**  
Bratislava, Slovakia

**M Moore**  
Guildford, UK  
(Local Organizer)

**K Papailiou**  
Athens, Greece

**W Riess**  
Hannover, Germany

**C T J Scrivener**  
Derby, UK  
(Local Organizer)

**C H Sieverding**  
St Genesius Rode, Belgium

**M Stastny**  
Plzen, Czech Republic

**J P van Buijtenen**  
Delft, The Netherlands

**A Wilson**  
Bergen, Norway

## Associated Organizations

**Associazione Termotecnica**  
Italy

**Belgian Society of Mechanical and  
Environmental Engineering**  
Belgium

**Koninklijke Vlaamse  
Ingenieursvereniging**  
Italy

**Institution of Engineers in Ireland**  
Ireland

**Société Française des Mécaniciens**  
France

**VDI-Gesellschaft Energietechnik**  
Germany

**Norwegian Society of Engineers**  
Norway

**Komitet Problemow Energetyki P.A.N.**  
Poland

**Association of Czech Mechanical  
Engineers**  
Czech Republic

**Slovenska Asociacia Strojnych Inzinierov**  
Slovakia

**Svenska Mekanisters Riskforbund**  
Sweden

**Royal Institution of Engineers in the  
Netherlands (KIVI)**  
The Netherlands

## Related Titles of Interest

<b>Title</b>	<b>Editor/Author</b>	<b>ISBN</b>
<i>Handbook of Mechanical Works Inspection – A Guide to Effective Practice</i>	Clifford Matthews	1 86058 047 5
<i>Process Fan and Compressor Selection</i>	John Davidson and Otto von Bertele	0 85298 825 7
<i>Steam Turbine Governing and Overspeed Protection</i>	IMechE Seminar 1998–10	1 86058 162 5
<i>Gas Explosions in CCGT and Steam Plants</i>	IMechE Seminar 1998–3	1 86058 169 2
<i>Installation Effects in Fan Systems</i>	IMechE Seminar 1997–14	1 86058 107 2
<i>Aerodynamics of Turbomachinery</i>	IMechE Seminar 1996–21	1 86058 051 3
<i>Energy Saving in the Design and Operation of Compressors</i>	IMechE Seminar 1996–13	0 85298 985 7

For the full range of titles published by Professional Engineering Publishing contact:

Sales Department  
Professional Engineering Publishing Limited  
Northgate Avenue  
Bury St Edmunds  
Suffolk  
IP32 6BW  
UK

Tel: 01284 724384  
Fax: 01284 718692

# Contents – Volume 1

## **Turbine Aerodynamics**

C557/063/99	<b>Aerodynamic performance of two isolated turbine stators in transonic annular cascade flow</b> K Freudenreich, M Jöcker, W Höhn, T H Fransson, and H-J Rehder	3
C557/011/99	<b>Numerical simulation of three-dimensional inlet guide vanes</b> V Michelassi and E Belardini	21
C557/039/99	<b>An experimental investigation into the three-dimensional flow field and loss mechanisms in a two-stage axial turbine</b> V Breisig, C Lerner, P Peters, H Pfof, and M Deckers	33
C557/055/99	<b>Measurements of turbine blade aerodynamic entropy generation rate</b> F K O'Donnell and M R D Davies	43
C557/093/99	<b>Multi-stage three-dimensional Navier–Stokes computation of off-design operation of a four-stage turbine</b> G A Gerolymos and C Hanisch	55
C557/022/99	<b>Throughflow analysis for cooled turbines</b> S Gehring and W Riess	79
C557/073/99	<b>Measurements of complex air flow phenomena inside the rotor of an operating industrial gas turbine</b> D Regnery, U Hoeppepner, N Vortmeyer, and K Nitsche	89

## **Design Methods**

C557/103/99	<b>The aerodynamic design and testing of a supersonic turbine for rocket engine application</b> U Wåhlén	101
C557/154/99	<b>Three-dimensional turbine blade design using a Navier–Stokes solver and Artificial Neural Network</b> S Pierret and R A Van den Braembussche	113
C557/043/99	<b>The role of research in the aerodynamic design of an advanced low-pressure turbine</b> N W Harvey, J C Cox, V Schulte, R Howell, and H P Hodson	123

## **Transition and Turbulence**

C557/142/99	<b>The prediction of flow on a flat plate with a circular leading edge under zero and non-zero pressure gradient</b> C Yakinthos and A Goulas	135
-------------	--	-----

C557/025/99	<b>Unsteady transition measurements using a Ludwig tube</b> R Schook, H C De Lange, and A A van Steenhoven	147
C557/036/99	<b>Calculation of transition in turbine cascades by conditioned Navier–Stokes equations</b> J Steelant and E Dick	157
C557/159/99	<b>Transition studies on a two-dimensional NACA63 isolated airfoil at high Mach numbers</b> S Svensdotter, J Hu, and T Fransson	167
C557/107/99	<b>Experiments on by-pass boundary layer transition with several turbulence length scales</b> P Jonas, O Mazur, and V Uruba	179
C557/131/99	<b>Modelling turbomachine-blade flows with non-linear eddy–viscosity models and second-moment closure</b> W-L Chen and M A Leschziner	189
C557/153/99	<b>Experiments on turbulent flow separation</b> B G B Muhammad-Klingmann and J P R Gustavsson	201
C557/143/99	<b>An effect of the curved passage depth on the shock- induced separation flow structure</b> J Czerwinska and P Doerffer	211
C557/139/99	<b>Unsteady flow past a turbine blade using non-linear two-equation turbulence models</b> F Magagnato	221
C557/068/99	<b>Investigation of wake-induced transition on a highly loaded low-pressure turbine cascade</b> S Brunner, L Fottner, V Schulte, and G Kappler	231
C557/084/99	<b>A new intermittency model incorporating the calming effect</b> O N Ramesh and H P Hodson	243
C557/130/99	<b>Turbulence modelling of rotor-stator interaction with linear and non-linear eddy–viscosity models</b> W-L Chen and M A Leschziner	259

## **Blade–Row Interaction and Aeroelasticity**

C557/057/99	<b>Experimental investigation of the unsteady rotor aerodynamics of a transonic turbine stage</b> R Dénos, C H Sieverding, T Arts, J F Brouckaert, G Paniagua, and V Michelassi	271
C557/049/99	<b>Three-dimensional unsteady Navier–Stokes analysis of stator–rotor interaction in axial-flow turbines</b> L He	289



C557/018/99	<b>Comparison of three approaches to model stator–rotor interaction in the turbine front stage of an industrial gas turbine</b> M von Hoyningen-Huene and J Hermeler	307
C557/017/99	<b>Stator wake clocking effects on three-dimensional unsteady flow in a two-stage low-pressure turbine</b> J E Krysinski, A Smolny, J R Blaszcak, and H E Gallus	323
C557/156/99	<b>Numerical analysis of wakes interactions in a transonic inviscid flow of compressor</b> G L Oliveira, P Ferrand, and S Aubert	333
C557/044/99	<b>Simulation of the unsteady interaction of coupled fans with ventilating systems</b> B Schulze Dieckhoff and T H Carolus	343
C557/114/99	<b>Viscous flutter calculations for a fan assembly using hybrid grids</b> M Vahdati, A I Sayma, and M Imregun	353
C557/116/99	<b>Flutter stability analysis of a bird-damaged fan assembly</b> E Ferrari, M Vahdati, and M Imregun	365
C557/067/99	<b>Forced response prediction within the design process</b> J S Green and J G Marshall	377

## **Erosion**

C557/092/99	<b>Novel design for a gas expander for highly particle loaded gases</b> E Zettl and H Jericha	395
C557/091/99	<b>Erosion due to particle impact in supersonic flow</b> R Pöschl, J Woisetschlager, and H Jericha	405
C557/118/99	<b>A pump separator of mechanical impurities</b> A Wilk and S Wilk	417

## **Secondary Flows and Tip Clearance Flows**

C557/135/99	<b>Horseshoe vortex control by suction through a slot in the wall cylinder junction</b> D P Georgiou and V A Papavassilipoulos	429
C557/027/99	<b>An experimental investigation of secondary flow in a low aspect ratio impulse cascade at different inlet flow angles</b> V Molnár, F Ridzon, and T Sporina	441
C557/060/99	<b>Profiled end-wall design for a turbine nozzle row</b> J Yan, D G Gregory-Smith, and N Z Ince	453

C557/144/99	<b>Tip-clearance-affected flow fields in a turbine blade row</b> M Sell, M Treiber, C Casciaro, and G Gyarmathy	465
C557/148/99	<b>Experimental and numerical investigations on the influence of the tip leakage flow on the radial flow field in a four-stage turbine</b> D Bohn, K Kusterer, and M Lamping	477
C557/088/99	<b>Parametric study of the flow in swirl brakes by means of a three-dimensional Navier–Stokes solver</b> K K Nielsen, C M Myllerup, and R A Van den Braembussche	489

## **Additional Paper**

C557/138/99	<b>Through-flow model for design and analysis integrated in a three-dimensional Navier–Stokes solver</b> A Sturmayer and Ch Hirsch	501
-------------	---	-----

# **Contents – Volume 2**

## **Compressors**

C557/106/99	<b>Concerted experimental and numerical studies on axial flow fan rotor aerodynamics</b> A Corsini, F Rispoli, F Bencze, and J Vad	519
C557/125/99	<b>Influence of flow coefficient on the turbulence characteristics in the flow behind a rotor blade row of an axial low-speed compressor stage</b> A S Witkowski, T J Chmielniak, M D Strozik, and M M Majkut	533
C557/100/99	<b>The nature of wakes in multi-stage axial flow compressors</b> S Read and R L Elder	545
C557/095/99	<b>Effect of stator design on stator hub boundary layer separation in a highly loaded single-stage axial flow low-speed compressor</b> J Friedrichs, S Baumgarten, and U Stark	573

## **Rotating Stall and Instability**

C557/061/99	<b>Experimental investigations of flow instabilities in a single-stage axial compressor</b> A Jördening, B Stoffel, and B Matyschok	585
C557/006/99	<b>Experimental investigation of rotating instabilities in a low-speed research compressor</b> R Mailach	595

C557/097/99	<b>Structure and propagation of rotating stall cells in an axial compressor stage</b> A P Saxer, H M Saxer-Felici, F Ginter, A Inderbitzin, and G Gyarmathy	605
C557/104/99	<b>An experimental study of stall in two axial compressor stages with variable inlet guide and stator vanes</b> V Cyrus	619

## Calculation Methods

C557/047/99	<b>Design of multi-stage axial flow turbines and compressors</b> C Bena, F Larocca, and L Zannetti	635
C557/147/99	<b>Numerical simulations of flows in components of turbomachines using various implicit methods</b> O Schmid, A Bußmann, E von Lavante, and M Moczala	645
C557/012/99	<b>Computations for internal flows with a low Mach preconditioned Newton–Krylov scheme</b> P Adami	655

## Steam Turbines

C557/158/99	<b>Temperature jet development in a cross-over channel</b> D Bohn, H-W Funke, and J Gier	671
C557/077/99	<b>Partial steam admission in an axial turbine stage</b> J Skopek, J Vomela, L Tajc, and J Polansky	681
C557/007/99	<b>Optimization of the inlet casing of a low-pressure steam turbine</b> A C Benim and M Geiger	693
C557/124/99	<b>Flow around the rotor blade tips of steam turbine last stage</b> M Stastny, R Matas, P Safarik, A R Jung, J F Mayer, and H Stetter	703
C557/042/99	<b>Velocity and pressure measurements in a non-stationary transonic steam flow</b> W Bosschaerts	713
C557/023/99	<b>Steady and unsteady flow measurements in the last stages of LP steam turbines</b> D Schmidt and W Riess	723
C557/112/99	<b>Three-dimensional coupled flow calculations in a low-pressure steam turbine last stage and exhaust hood for nominal and partial load conditions: comparisons with experimental results</b> F Déjean, C Marty, and O Hartmann	735

C557/041/99	<b>New principles of exhaust duct designing and updating</b> A Zaryankin, A N Paramonov, S I Chusov, and B P Simonov	747
C557/024/99	<b>Examination of the dynamic stress in the moving blades of the last stage in a low-pressure model turbine during windage</b> F Truckenmüller, W Gerschütz, H Stetter, and H-G Hosenfeld	757

## Condensation

C557/019/99	<b>Modelling of the droplet size distribution in LP steam turbine</b> V Petr and M Kolovratnik	771
C557/099/99	<b>Wet steam analysis using Eulerian method for two-dimensional droplet growth and nucleation rate equations</b> G Singh, R Hunt, and McCallum	783
C557/123/99	<b>Steam flow calculations in turbine channels</b> T Chmielniak, W Wroblewski, and S Dykas	803
C557/082/99	<b>Numerical analysis of heterohomogeneous condensation of the steam flowing in turbine cascade</b> M Stastny and M Sejna	815
C557/010/99	<b>Method for nucleating steam flow in low-pressure turbine stages</b> U Singh	827

## Radial Compressors

C557/065/99	<b>Performance prediction and optimization of an industrial centrifugal compressor inlet guide vane system</b> M Coppinger and E Swain	839
C557/134/99	<b>Impact of leading edge redesign on vaned radial diffuser performance</b> E Casartelli, A P Saxer, and G Gyarmathy	853
C557/075/99	<b>Time-resolved measurements with fast-response probes and laser-Doppler velocimetry at the impeller exit of a centrifugal compressor – a comparison of two measurement techniques</b> W P Gizzi, C Roduner, D Stahlecker, P Köppel, and G Gyarmathy	865
C557/111/99	<b>Research into variable geometry turbochargers without wastegates</b> M Toussaint, G Descombes, and M Pluviose	883

## Radial Machines

C557/028/99	<b>Surge dynamics in a centrifugal compressor system</b> C Meuleman, R de Lange, and A van Steenhoven	895
C557/030/99	<b>Unsteady characteristics of a mixed-flow turbocharger turbine</b> C Arcoumanis, N Karamanis, R F Martinez-Botas, and C C Su	905
C557/001/99	<b>An analysis of the internal aerodynamic losses produced in the laminar and centrifugal flow between two co-rotating discs</b> E Laroche and Y Ribaud	923

## Heat Transfer and Cooling

C557/119/99	<b>Experimental investigation of the external heat transfer on a nozzle guide vane</b> U R Radeklint, C Hjalmarsson, F Rubensdörffer, and M Annerfeldt	937
C557/150/99	<b>An experimental investigation of the interaction between trailing edge coolant-jet and blade wake</b> P Zunino, M Ubaldi, A Cattanei, and U Campora	953
C557/074/99	<b>Prediction of flow and heat transfer in a stationary two- dimensional rib roughened passage using low-<i>Re</i> turbulent models</b> J Bredberg and L Davidson	963
C557/078/99	<b>PIV investigation of the flow characteristics in an internal coolant passage with 90 degree rib arrangement</b> J Schabacker, A Böls, and B V Johnson	973

## Pumps and Hydraulic Turbines

C557/034/99	<b>Evaluation of predictive capabilities of a performance prediction model for pumps of various specific speeds handling oil and water</b> A Nemdili and D-H Hellmann	987
C557/045/99	<b>Numerical investigations of the flow in a pump turbine in pump mode</b> F A Muggli, K Eisele, Z Zhang, M V Casey, H Keck, A Sebestyen, and M Sallaberger	997
C557/102/99	<b>Numerical and experimental investigation of flow in axial flow hydraulic machinery</b> M Sedlar, M Vlach, and J Soukal	1007
C557/083/99	<b>Investigation of rotor-stator interaction influence on flow fields in radial flow pumps</b> M Sedlar and P Mensik	1017

C557/080/99	<b>Performance discontinuity of a shrouded centrifugal pump impeller: Part 1 – numerical model and flow instability</b> F Ginter and T Staubli	1027
C557/080/99	<b>Performance discontinuity of a shrouded centrifugal pump impeller: Part 2 – stabilizing geometrical modifications</b> F Ginter and T Staubli	1039
C557/066/99	<b>Experimental and numerical analysis about self-priming phenomena on waterwork-pump systems</b> G Navarro and L Tosato	1051

## **Performance**

C557/098/99	<b>Small gas turbine design: a total technology educational experience</b> A W Court, K R Pullen, and C B Besant	1063
C557/002/99	<b>Increased data reliability by data validation during performance tests and field acceptance tests on combustion engines</b> W Götz and S Reisacher	1075
C557/141/99	<b>On thermal diagnostics of turbomachinery power systems</b> J Gluch and J Krzyzanowski	1087
C557/149/99	<b>Gas turbines – modelling and simulation</b> A Miller, J Lewandowski, K Badyda, and K Swirski	1099

<b>Authors' Index</b>		1109
-----------------------	--	------

# Compressors





## Concerted experimental and numerical studies on axial flow fan rotor aerodynamics

**A CORSINI and F RISPOLI**

Dipartimento di Meccanica e Aeronautica, University of Rome, Italy

**F BENCZE and J VAD**

Department of Fluid Mechanics, Technical University of Budapest, Hungary

### SYNOPSIS

The paper reports a concerted application of experimental (Laser Doppler Anemometry, LDA) and Computational Fluid Dynamics (CFD) techniques for an investigation of the high average total head rise axial flow fan rotor of non-free vortex design. The LDA data have been used as inlet boundary conditions for CFD calculations as well as a basis for verification of computational results. From a comparison of outlet LDA and CFD data, possible improvements in the computational technique have been pointed out. The interblade CFD results supplied guidelines for improvement in the rotor cascade design method.

### NOTATIONS

#### Latin letters

$c$	absolute velocity
$c_{\varepsilon 1}, c_{\varepsilon 2}$	turbulent dissipation rate production constants
$d$	prescribed Dirichlet boundary conditions
$f$	residual forces vector
$k$	turbulent kinetic energy
$\ell$	blade chord
$n_j$	normal vector Cartesian components
$p$	pressure
$r$	radius
$R = r/r_c$	dimensionless radius
$t$	blade pitch
$u_c$	reference velocity ( $r_c \cdot \omega$ )
$u_i$	relative velocity Cartesian components
$\overline{u_i' u_j'}$	Reynolds stress tensor
$v$	prescribed Neumann boundary conditions

#### Greek letters

$\gamma$	blade stagger angle
----------	---------------------